Digital electromagnetic actuators array

L. Petit, C. Prelle, E. Doré and F. Lamarque

Abstract— **This paper presents the design of an array composed of 5 × 5 digital electromagnetic actuators which each one having four discrete positions and two orthogonal displacement axes. This work is composed of two parts: firstly, the elementary digital actuator is defined using the experience of a previous study and secondly, the array is designed by taking into account the magnetic and electromagnetic interactions between the elementary actuators.**

I. INTRODUCTION

MECHANICAL and mechatronic systems are becoming more and more complex due to the need of reduced size and increased functionalities. Their performances and reliability levels are also increased imposing to add sensors and complexify the control. As a consequence, their physical integration in other mechanical systems is very difficult causing higher costs.

In all mechanical systems, actuators represent important elements because they realize an action, as a force or a displacement, in response to the control. In order to bring a solution to the mentioned problem, digital actuators can be used instead of analogical actuators in mechanical systems. Indeed, digital actuators are based on an architecture composed of discrete positions, theoretically well known and repeatable [1], between which the mobile part switches. With this property, digital actuators can be controlled via open loop control [2] and no sensor is theoretically needed which makes the integration easier in mechanical systems. Moreover, the energy consumption of these actuators is low because energy pulses are only provided during the switch between the discrete positions [3]. The Joule effect is then also reduced. The main drawback of the digital actuation concerns the stroke which is fixed at the manufacturing step. However, an assembly of several digital actuators allows variable strokes [2].

The applications of digital actuators can be classified into two categories: the elementary applications, composed of only one actuator, and the complex ones, composed of an array of several actuators. The main elementary application concerns the realisation of optical [4], electrical [5] or fluidic switches [6]. The complex applications regroup displacement devices [7]-[8], tactile display devices [9], modular robot [10], digital-to-analog converters [11] or mechanical memories [12].

In the literature, most of the digital actuators dispose of two discrete positions and one displacement direction. The originality of the presented work concerns the architecture of the elementary actuator which has two orthogonal displacement directions and four discrete positions. In a previous study, an elementary four discrete positions electromagnetic actuators was developed and tested [13]-[14]. The work presented in this paper concerns the design of an array composed of 5 × 5 digital electromagnetic actuators in order to realize complex tasks. In this paper, the elementary actuator is firstly presented with taking into account of the previous study and secondly the design of the array is detailed while considering the magnetic and electromagnetic interactions between the elementary actuators.

II. ELEMENTARY DIGITAL ACTUATOR

A. *Principle*

The elementary actuator is composed of five Permanent Magnets (PMs): one mobile and four fixed (Fig. 1). The Mobile Permanent Magnet (MPM) is placed in a square bracket and can attain the four corners of the bracket which are the four discrete positions of the actuator. To switch between these positions, two orthogonal electric wires are placed beneath the bracket. When a current passes into a wire, an electromagnetic force (Lorentz force) appears because of the flux density from the MPM which ensures the switch of the MPM between two discrete positions. A thin glass layer is placed between the MPM and the wires in order to avoid electrical contact between them. The two wires are manufactured on both sides of a Printed Circuit Board to avoid electrical contact between them. Its thickness has also been chosen to be as small as possible (200 µm) to minimize the difference between the two wires. One wire, called Upper Wire (UW), is then placed nearer (d_2) to the MPM than the other one (d_3) called Lower Wire (LW). Moreover, the gap between the MPM and the square stop corresponds to the stroke of the digital actuator. To ensure MPM holding at each discrete position without energy input, four Fixed Permanent Magnets (FPMs) with magnetization oriented in the opposite direction as compared to MPM are placed around the square stop in order to generate a magnetic attraction on the MPM when it is in discrete positions.

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For the definition of the elementary actuator, a semi-analytical model has been used. This one computes the magnetic and electromagnetic forces exerted on the MPM and gives its displacement between two discrete positions. It has been described in [13]-[14] and was used to predict and validate experimental results.

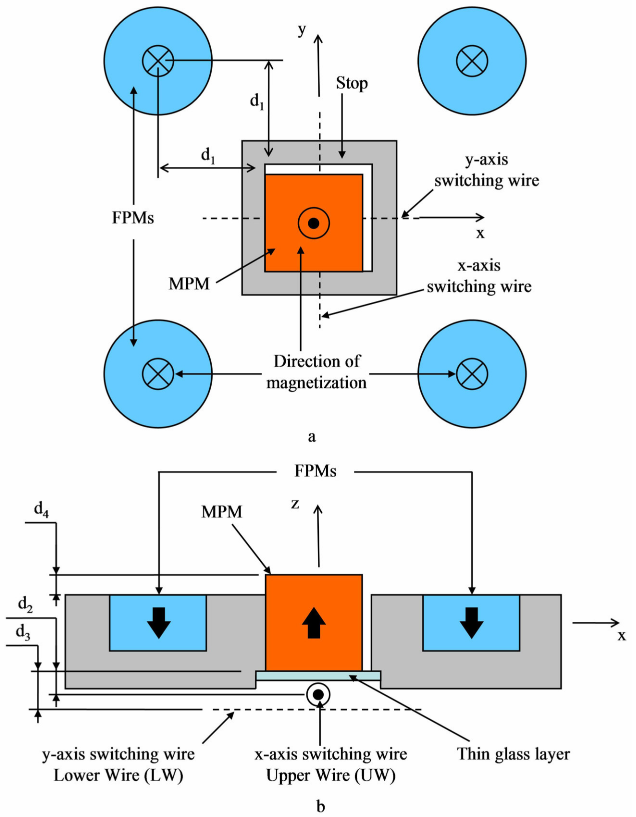

Fig. 1. Principle of the elementary digital actuator - a. Top View, b. Side view

B. *Properties*

The presented work corresponds to the first step of the array design and one objective is to validate the functioning of an experimental prototype. For this first work, we decided to manufacture the prototype with conventional machining and after the validation we encouraged to use micro-fabrication to manufacture a micro-array. The properties of the elementary actuator were defined by considering conventional machining and are given in Table I. The MPM dimensions have been chosen in relation with the smallest square bracket dimension that we can manufacture (2 mm). The MPM magnetization corresponds to the highest value in order to obtain a high electromagnetic force (Lorentz force). The FPM magnetization has been chosen by taking into account the interactions between the elementary actuators and will be explained in Section III.B. Cylindrical FPMs were chosen in order to facilitate the manufacturing. The stroke of the MPM was fixed as small as possible in order to obtain a high displacement resolution. However, this value should not be too small because of the manufacturing errors on the MPM and square bracket dimensions. A 0.2 mm stroke has then been chosen.

TABLE I
PROPERTIES OF THE ELEMENTARY ACTUATOR

Magnet	Dimensions	Magnetization
MPM	2 mm × 2 mm × 2 mm	1.45 T
FPMs	Ø2.26 mm × 1.25 mm	1.45 T
	MPM Stroke	
	0.2 mm	
	Distances	
	d_1	3.85 mm
	d_2	222 µm
	d_3	458 µm
	d_4	375 µm

C. *Holding force value*

For a given magnetization, the holding force value is fixed by the position of the FPMs from the stop (d_1 in Fig. 1). For a digital actuator, this force corresponds to an important parameter because it characterizes the behaviour of the actuator. The Figure 2 represents the principle of a digital actuator with two discrete positions in two configurations: with high (Fig. 2.a) and with low (Fig. 2.b) holding force. In the Figure, the inclined zone (d_{max}) represents the zone where the mobile part returns in discrete position without current because of the magnetic holding force. If the mobile part is placed in the middle of the stroke (horizontal zone), it stays in this position because of friction effects. With a high holding force, d_{max} increases and vice-versa.

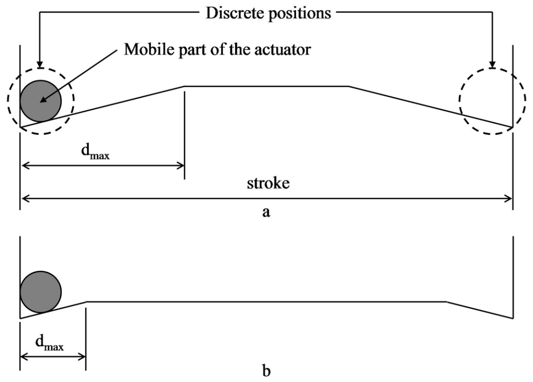

Fig. 2. Representation of d_{max} for a digital actuator with a high holding force (a) and with a low holding force (b)

During a switch between two discrete positions, the MPM is in contact with the thin glass layer on its bottom side and with the stop on its lateral side. In previous studies, we have determined experimentally the friction coefficients corresponding to these two contacts and validated them by comparing experimental and modelling results. For the presented actuator, the value of the total friction force is 0.42 mN.

Fig. 3 represents d_{max} in function of the holding force value. In this Figure, we observe that when the holding force is lower than the friction force (< 0.42 mN), d_{max} is null, which means that if the MPM is lightly displaced from the discrete position, it doesn't return in discrete position because of the friction effect. When the holding force is higher than the friction force, the distance increases and tends towards 0.1 mm which corresponds to the half of the stroke. When the holding force is high, the behaviour of the actuator is then improved. However in this configuration, the driving current, to switch the MPM between the discrete positions, should be high which increases the energy consumption.

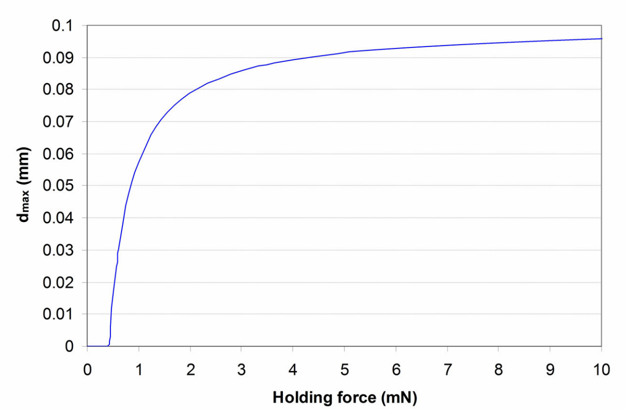

Fig. 3. Evolution of d_{max} in function of the holding force value

For the presented actuator, a compromise has been done between the actuator behaviour and the energy consumption. The holding force value has been fixed at 0.6 mN which ensures a distance d_{max} of 29 µm.

D. *Characteristics of the elementary actuator*

Fig. 4 represents the force along the displacement direction exerted on the MPM in function of its position between two discrete positions (located at ±0.1 mm) for three driving current values: 0 A, 1 A and 3 A. For each current value, two configurations are represented: using the UW and the LW.

In Fig. 4, we observe that when there is no driving current, the holding force in discrete position is ±0.6 mN. When a 1 A driving current is used, the previous curve is shifted upward and the value of this shift represents the added electromagnetic force (Table II). The electromagnetic force generated by using LW is 19% less than using UW for same current value. This difference is explained by the flux density value from the MPM which is lower for the LW than for the UW because the LW is located far (d_2) from the MPM than the UW (d_3). However, if the same electromagnetic force is needed along the two axes, the current in the LW should be 19% higher than the current in the UW in order to compensate the lack of flux density.

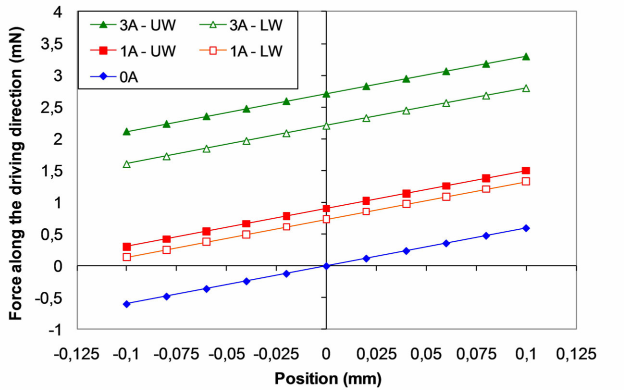

Fig. 4. Evolution of the force along the displacement direction in function of the MPM position between two discrete positions for different driving current values (0 A, 1 A and 3 A) with using the UW and LW

TABLE II
ELECTROMAGNETIC FORCE VALUES

Driving current	Electromagnetic force	
	UW	LW
1 A	0.90 mN	0.73 mN
3 A	2.71 mN	2.20 mN

III. DIGITAL ACTUATORS ARRAY

After the elementary digital actuator definition, the array has been designed. In order to obtain a symetrical array, an arrangement of 5 × 5 elementary actuators has been selected. Moreover to reduce the size of the array, the FPMs of two adjacent elementary actuators are shared. For the array design, the RADIA® software has been used because it can consider many PMs easily.

A. *Holding force homogenization*

One objective of the design is to obtain a homogeneous behaviour of all the elementary actuators. Fig. 5 represents the holding force, along the x-axis, exerted on each MPM when all of them are placed in the (–x , –y) position.

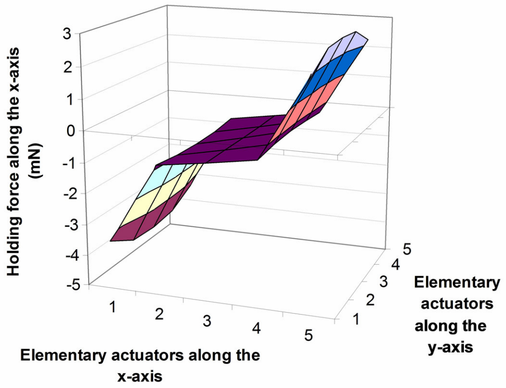

Fig. 5. Representation of the holding force exerted on each MPM ("Config 0")

The holding force is almost homogenous for the elementary actuators placed in the middle of the array (row 2, 3 and 4 along the x-axis). These actuators have other elementary actuators as neighbours on both sides in the x-direction, they are then almost magnetically equilibrated. For these actuators, the holding force is about 0.6 mN, which correspond to the value previously defined. For the actuators placed in row 1 or 5, the amplitude of the holding force exerted on them is very high (≈ 3 mN). Indeed, the elementary actuators placed on the array sides are not magnetically equilibrated because there are no elementary actuators at one side of them in the x-direction (side –x for row 1 and side +x for row 5). In this configuration, the maximal holding force variation between the elementary actuators is 6.8 mN.

In order to improve the holding force homogeneity and to magnetically equilibrate the elementary actuators placed at the sides of the array, fixed PMs were added around the 25 elementary actuators (Fig. 6). Two types of PMs are added: the first ones correspond to PMs which replace MPMs (MPM added) (Config 0 → Config 1 in Fig. 6) and the second one to PMs which replace FPMs (FPM added) (Config 1 → Config 2 in Fig. 6). Eight configurations were studied (Config 0, Config 1, Config 2, Config 3, Config 4, Config 5, Config 6 and Config 7), and one type of PMs are added between each configuration (Fig. 6).

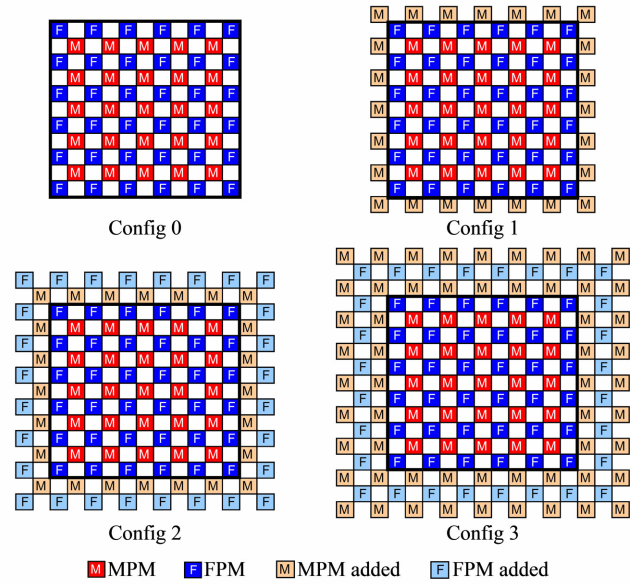
Config 0
Config 1
Config 2
Config 3

Fig. 6. Representations of Config 0, Config 1, Config 2 and Config 3

Fig. 7 represents the maximal holding force variation between the elementary digital actuators for the different studied configurations. The "Config 0" corresponds to the variation observed in Figure 5 without PMs added, for which the maximal variation between the actuators is 6.8 mN. For "Config 1", added PMs which replace MPMs (MPM added) are placed around the elementary actuators and the variation is highly reduced (6.8 mN → 0.4 mN). For "Config 2", added PMs which replace FPMs (FPM added) are placed around the "Config 1" and the variation is increased (0.4 mN → 0.8 mN). Indeed, the FPMs magnetization is oriented in the opposite direction than the one of MPMs which explains a variation in the opposite direction. From Fig. 7, its is preferable to choose a configuration between "Config 1", "Config 3", "Config 5" or "Config 7". Moreover, from "Config 3" the addition of more PMs has a very small effect on the maximal holding force variation. In order to minimize the number of PMs and the size of the array, the "Config 3" has been choosen. With this one, the maximal holding force variation represents 0.15 mN (Fig. 8).

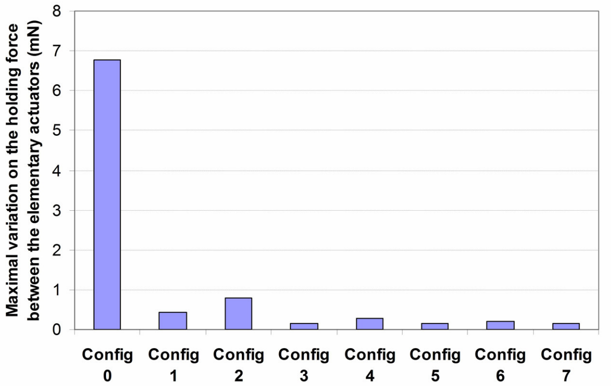

Fig. 7. Evolution of the maximal holding force variation between the elementary actuators in function of the configurations studied

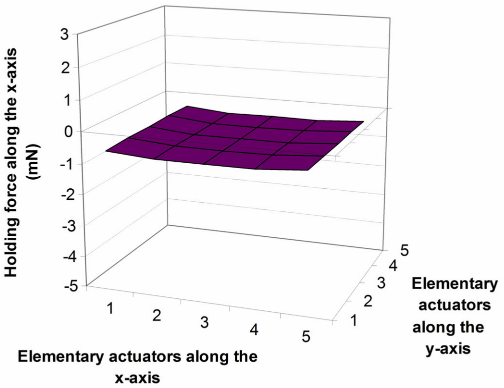

Fig. 8. Representation of the holding force exerted on each MPM ("Config 3")

For this study, the added PMs (MPM added and FPM added) are to the same ones used for the elementary actuators. These PMs represent exactly elementary actuators (Fig. 6) which simplifies the array architecture. As perspective we consider optimizing this configuration by using PMs different than MPM and FPM (dimensions and magnetization value) and placed differently in order to reduce the number of added PMs and the size of the array.

B. Choice of the FPMs magnetization

The MPM magnetization was chosen in order to maximize the electromagnetic force generated when a current passes inside a wire. For the FPMs, a study has been realized with the maximum (1.45 T) and minimum (1 T) magnetization values proposed by our PM manufacturer. In this study, the holding force is constant (0.6 mN) and the distance d_1 between the FPMs and the stop has been adapted in function of the magnetization value. For the two studied configurations, the maximal holding force variation on the 25 elementary actuators has been determined (Table III).

TABLE III
STUDY OF THE FPMS MAGNETIZATION

Magnetization	d_1	Holding force	Variation
1 T	3.51 mm	0.6 mN	0.31 mN
1.45 T	3.85 mm		0.15 mN

When the FPMs magnetization is low (1 T), the maximum variation of the holding force is high (0.31 mN) and inversely (0.15 mN with 1.45 T). Indeed with a low magnetization value, the distance d_1 is short (3.51 mm). In this case, the elementary actuators, then the MPMs, are closer to each other. The interaction between MPMs is then more important which explains the variation value. The highest magnetization value (1.45 T) has then been chosen for the FPMs.

C. Electromagnetic disturbances

When the array is used, the elementary actuators should be controlled independently that imposes to quantify the electromagnetic disturbances generated by a switched MPM on its neightbours. When an elementary actuator is switched with a 3 A driving current (nominal value), the electromagnetic disturbance on its most disturbed neightbours is 0.03 mN. This disturbance is then not enough high to generate a non-desired switch because it represents only 4.9% of the holding force value.

D. Experimental prototype

An experimental prototype of the actuators array has been manufactured (Fig. 9). It is composed of an aluminum part manufactured with conventional machining. On Fig. 9, the 5×5 elementary actuators are indicated and the PMs added (Config 3) are visible. This array is composed of 145 PMs (25 MPMs, 36 FPMs, 56 MPM added and 28 FPM added). For the wires, the PCB technique was used. In order to avoid positionning error, all the wires were printed on the same circuit (non visible on Fig. 9).

IV. CONCLUSION AND PERSPECTIVES

In this paper, the design of a 5×5 digital electromagnetic actuators array is presented. In a first part, the elementary actuator has been defined and in a second part the array has been designed by taking into account of the magnetic and electromagnetic interactions between the elementary actuators. A prototype of this array was manufactured and will be tested experimentally. The objectives of this test are to validate the independent functionning of the elementary actuators and to qualify their performances. After this validation, we envisage to use micro-fabrication to manufacture a micro-array.

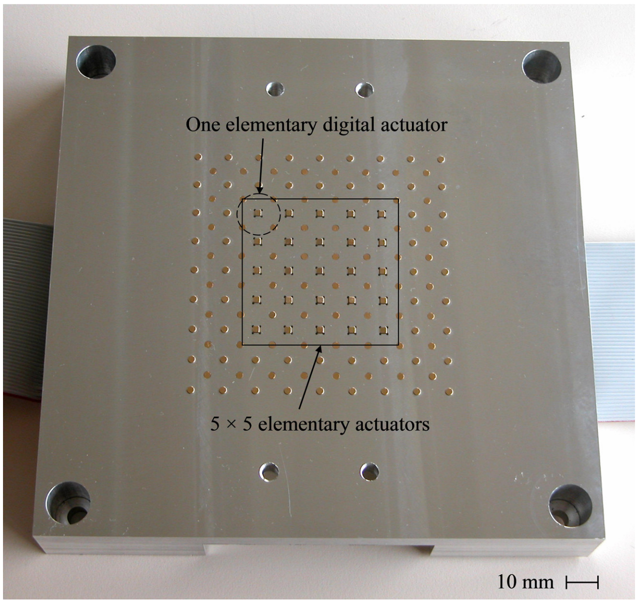

Fig. 9. Overall view of the experimental prototype

In future, another perspective is to use this type of array as a plane displacement device by placing a plate on the top side of the array which will be in contact with all of MPMs. When all of them will be switched simultaneously in one direction, the plate will be displaced from a distance corresponding to the stroke of the elementary actuators. Next, they will come back in the initial position alternativelly. During this phase, the plate will not move because of the friction effect between it and the other MPMs. Finally, when all of the MPM were come back in the initial position, a second step can be realized. The plate movement is then obtained using the stick-slip principle.

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